740767

HIGH ALTITUDE OBSERVATORY
of
Harvard University and University of Colorado

Technical Report

SOLAR ACTIVITY AND THE YELLOW CORONAL LINE 5694 A.

by

Frederick P. Dolder

(A thesis submitted in partial fulfillment
of the requirements for the degree
Master of Science, Department of Physics
University of Colorado.)

10 November 1952

ONR Contract Nonr-393 (02)

Project NR 046-721/9-22-52

FOREWORD

In accordance with our initial plans, a part of the research work under ONR Contract Nonr-393 (02) has been conducted by a graduate student in the University of Colorado, Mr. Frederick P. Dolder. The following document is a copy of the thesis resulting from that work. The thesis has been submitted to the Faculty of the Graduate School of the University of Colorado and has been accepted.

The principal scientific results described in this thesis will later be made the subject of published articles in the technical literature. These published articles will be submitted as additional technical reports under this contract, since it is probable that additional results will be included therein.

Walter Orr Roberts, Director
High Altitude Observatory

10 November 1952

CONTENTS

ABSTRACT

An examination of the coronal and prominence emission spectrograms containing all known cases of the yellow coronal emission line (5694 A.) taken at the Climax and Sacramento Peak Observatories revealed that prominences accompanied each yellow-line emission and that about 80% of these prominences showed abnormal sightline velocities. It also showed that in a large number of cases the red (6374) and green (5303) coronal lines had maxima at the position at which the yellow line was observed. Doppler shifts were present in the red coronal line in 10% of the cases examined and a small number of Doppler shifts in the green and yellow line were also seen. Except for these cases of Doppler shifts in coronal lines, the phenomenon is practically absent in Climax and Sacramento Peak spectra.

Analysis and comparison by simple statistical procedures of the prominences occurring at the time of the yellow line and prominences occurring far from the time of the yellow line showed that a significant and easily recognizable difference existed between the two types of prominences.

A study of the number of limb flares accompanying the yellow line revealed that the phenomena are, beyond all question, associated in time and location, suggesting that a definite physical relationship exists between the flares and the yellow line. The nature of this relationship could not be determined.

The observations lead to the speculation that location of the principal maxima of coronal intensity might be possible from observation of the more easily seen prominences. There is also a possibility of predicting the arrival of flare-producing regions by limb observations of the corona.

I. INTRODUCTION

At the time of a solar eclipse, when the moon hides the brilliant surface of the sun, we are able to see the faint, silvery-white corona that makes up a principal part of the sun's atmosphere. The corona, as seen at eclipse, actually appears quite bright to the eye, and extends to heights of several million miles. It shows different spectroscopic and optical characteristics at different distances from the sun. Far out from the solar limb the coronal light is dominated by a continuous spectrum containing Fraunhofer absorption lines. This portion of the corona is probably due to scattering of sunlight by cosmic dust, and in the strict sense is not solar corona at all, but evidence of interplanetary "dust". This component of the corona probably is identical with the zodiacal light. Close to the sun, within a radius or so, the coronal spectrum has emission lines from the highly ionized atoms of iron, nickel, calcium, and argon. At distances extending to several solar diameters from the sun, the corona has a continuous spectrum without absorption lines exhibiting rays and streamers, and also showing appreciable polarization. This component is attributed to Thompson scattering of sunlight by high velocity electrons. The Doppler effect of the fast-moving electrons "smears" out the absorption lines of the sunlight. Recent work by Woolley and Allen 1) and H. van de Hulst 2) has greatly improved our knowledge of the separation of these three components of the sun's corona.

I am interested in the emission spectrum portion of the corona, and in particular in the emission line at 5694 A., the yellow coronal line. Of the some 25 coronal emission lines, only a few have not been identified with reasonable certainty. The yellow line is the most important of this small group of unidentified lines. Bernard Lyot 3) made the initial discovery of the yellow line in 1937 at the Pic du Midi Observatory during an early investigation of the coronal spectrum with his coronagraph. Since then the line has been reported many times, but never with any great regularity. It has, however, never been detected at eclipses.

On 26 February 1946, after four years of observing the corona daily, weather permitting, W. O. Roberts found the yellow line on a plate taken at the Fremont Pass Station of the Harvard College Observatory at Climax, Colorado. This was the first of some fifty observations of this line that have been made during the past six years at Climax and its sister station at Sacramento Peak in New Mexico.

The yellow line shows marked differences from the two most easily observed coronal lines in the visible range, the green line at 5303 A., and the red line at 6374 A. These two lines are visible at every observation of the corona and usually extend for great distances along the limb of the sun. They show broad profiles of intensity against wavelength, and change relatively little in total intensity from day to day. The yellow line shows the broad profile of a coronal line but there the similarities end. During its rare appearances it is confined to a small range of latitude and its visible lifetime is short, usually only one day but sometimes as long as three days. It is usually much weaker than

the red or green lines, often appearing as a very faint mark on the spectrogram. Because of this faintness, the atmospheric conditions must be excellent for the line to be seen. Dust, snow, or other particles in the air, scatter the light from the disk of the sun into that portion of the image where the corona lies, hiding this faint line in the scattered continuum.

The yellow line has been reported by several workers as being closely associated with prominences.[4, 5, 6] The green coronal line and a number of other lines are relatively independent of prominences. The red coronal line occasionally shows marked discontinuities in intensity in the region of certain prominences.

There have been many attempts to group the coronal lines into classes according to their behavior at the various eclipses. This was done in early efforts to identify the lines. The groups were made by associating those lines which had maxima and minima at the same latitude and whose intensities showed similar changes in height from the limb. The groups determined from the results of different eclipse expeditions were often contradictory, and it was not until the development of the coronagraph that a consistent grouping was made. Lyot, using a large amount of data collected over a period of several years, found that there seemed to be three recognizable groups.[3] The first group contained the green line at 5303 A.; the second, the red line at 6374 A.; and the third group was the yellow line itself. Looking back, it is interesting to note that the lines were not grouped according to the element from which they arose, but according to their ionization potentials as determined by Edlen three years later.[7] The group containing the green line was made up of iron and nickel lines having ionization potentials of between 325 and 422 E.V. The group with the red line contained two lines, both from iron, with ionization potentials of 233 and 261 E.V. Waldmeier[8] has reported that the yellow line at some times seems to be clearly associated with maxima of the green line, while I have seen many cases on the Climax spectra where it seems to be clearly associated with maxima of the red line. There are also many cases in which it seems to be clearly associated with maxima of the red line. There are also many cases in which it seems to be associated with neither of these lines. For this reason it is appropriate to assign a category of its own to the yellow line.

In 1942 Edlen presented a paper in which he identified 17 of the coronal lines as rising from forbidden transitions in highly-ionized atoms of iron, nickel, calcium, and argon.[7] At the same time he offered two tentative identifications, one of these being for the yellow line. He suggested that it might arise from the transition $2p^2$, $^3P_1 - {}^3P_0$ in Ca XV. The result had been obtained after a different extrapolation and was considered unreliable. There were several other reasons for calling this identification tentative. The ionization potential required for Ca XV is 814 E.V., which is considerably higher than that of any of the other coronal lines. He also felt that there should be another coronal line in the visible range arising from the transition $2p^2$ $^3P_2 - {}^3P_1$ which had not been found at that time, but he did not attempt to predict the expected wavelength. Recently Waldmeier[9] reported the discovery

of a coronal line at 5445 A. which appeared only with the yellow line, and which seemed to behave in a similar manner to the yellow line. He suggested that this line might be the missing line of Ca XV.

Shklovsky, of the Crimean Astrophysical Observatory, recently stated, on theoretical grounds, that the identification of the yellow line as Ca XV is probably not correct and suggested that this line, along with the line at 5445 A., might arise from some transition in Ne VI. [10]

At the meeting of the American Astronomical Society in June of 1951, Naqvi presented a paper in which he examined several of the difficulties of the Edlen identification. [11] He agreed that there should be another line besides the one at 5694 A. if the Edlen identification is correct, and predicted that the wavelength should be in the range of the two unidentified coronal lines at 4586 A. and 4567 A. He suggested that simultaneous observations of these three lines would have to be made to confirm or reject this identification.

Using refined methods, Garstang very recently showed that the wavelengths to be expected from the transitions $2p^2\ {}^3P_2 - {}^3P_1$ and $2p^2\ {}^3P_1 - {}^3P_0$ of Ca XV would be 5380 A. and 5480 A. respectively, with accuracy most probably within 50 A. either way. [12] He suggests, therefore, that the identification of any of the lines at 4567, 4586, 5445, and 5694 A. as arising from Ca XV is probably not correct.

In summing up the results of the work done on the identification of the yellow line, it is seen that there is still considerable doubt as to its atomic origin. The yellow line's connection with prominences seems to indicate that a low ionization potential is needed, though its very broad profile would indicate high excitation. The theoretical attempts at identification would seem to be contradictory at this time. Further studies of the observational material may lead toward an answer. Meanwhile study of the behavior of the line, and its association with active solar regions indicates that it is a most important line, and so efforts to identify it should be given careful attention. Several observational approaches to the study of the behavior of the yellow coronal line are open to us. The studies may even assist in the identification of the line, and will certainly aid in interpretation of the physical processes involved in its formation, once the identification is successfully carried out. One observational approach is to try to establish what unique attributes, if any, characterise the prominences that accompany the yellow line. Waldmeier has reported strange anomalies in these prominences, such as the presence of the line of He II or 5412 A., requiring high excitation at the same time as the B lines of magnesium and ionized iron of low excitation. [9] Another approach would be to establish the relationship between the yellow line and flares, which, according to Waldmeier [6] and Roberts [5] appear together. I have undertaken these two approaches in pursuit of the objectives of my research, and the results of my work make up the body of this thesis.

II. CHARACTERISTICS OF PROMINENCES AND FLARES

Prominences are gaseous clouds visible above the surface of the sun, consisting of hydrogen, helium, calcium, iron, and some other metals. The prominence emission spectrum shows very strong lines at Hα and the H and K lines of ionized calcium with weaker lines of helium, iron, magnesium, and sodium. Although their brightness per unit wavelength, even at the emission wavelength is considerably less than that of the photosphere, the prominences can be seen clearly at eclipses with the naked eye, or with a coronagraph fitted with narrow-band filters. The usual method of observing prominences outside of eclipse is to isolate one of the emission lines and observe the prominence in this monochromatic light. The usual practice (first applied by Robert R. McMath of McMath-Hulbert Observatory), is to obtain lapse-time pictures at short intervals of one to a few pictures per minute that show that the prominence material often is in very rapid motion.

These prominence clouds are usually classified according to their motion, shape, or spectrum. Pettit's classification by motion and shape is the system most often used,[13] though Secchi, many years ago, distinguished between active and quiescent prominences. In this classification there are six types of prominences, as follows:

I. Active

II. Eruptive

III. Sunspot

IV. Tornado

V. Quiescent

VI. Coronal

The quiescent prominences, as their name implies, are relatively inactive. They often look like a haystack sitting on the surface of the sun. These stable prominences sometimes last for days with little change in outline and showing only slight motion in their internal structure. When seen in projection on the solar disk they show as long, dark filaments. The active prominences, on the other hand, show considerable motion and generally send matter from the body of the prominence toward some center of attraction on the solar surface. Another class of rapidly moving prominence is the group called "sunspot prominences."" The prominence material of the sunspot prominences seems to appear in space and stream down toward a center of attraction. Delicate streamers or isolated knots of matter, moving rapidly as they form in space, rain toward the sun. Sometimes complete loops form with the prominence material moving down the two branches from a common source at the top. The velocities in the sunspot prominences are considerably higher than those seen in

the ordinary active prominences or the quiescents. Associated with sunspot prominences are the "surges", ejections of matter from the solar surface that frequently erupt from the focus of the sunspot prominence activity. The surges occasionally reach velocities as high as 500 km/sec., but the material usually falls back into the sun along the same path it took going out, in contrast to the true "eruptive" prominence which sends at least a major part of its matter out into space.

My first effort has been to try to distinguish whether a separation of prominences according to type, either by the Pettit scheme or others, suffices to isolate the prominences associated with the yellow coronal line from prominences in general.

The second portion of my investigation is to try to find out the relationship between the yellow line and solar flares. Such work promises not only help in the identification of the yellow line, but may assist our understanding of the mysteries of flares. Flares are a special class of explosively sudden and intensely brilliant prominences. The flares can be seen in the disk of the sun as bright features - the only prominences so observable. Some workers do not class flares with the prominences, but regard them as a separate class of solar phenomena. The mechanism of a flare is not understood, but a great deal has been written about the way a flare behaves. Richardson reports that 99% of the flares observed at Mount Wilson in the 15 years from 1935 to 1950 have occurred in the immediate neighborhood of a sunspot, with the highly complex spot groups producing more flares than the simple groups. 14)

Flares are often classified according to their maximum intensity or maximum size. Accurate photometry of flares has been done only for a most limited number of flares. However areas as a function of time and maximum areas are available for large numbers of flares over a substantial number of years. Flares are generally classed according to their "importance" on a scale of 1 to 3. Flares with areas of from 0 to 300 millionths of the visible sun's hemisphere fall in the class called "Importance 1." Those with areas of from 300 to 750 millionths fall in Importance 2, and those with areas larger than 750 millionths fall in Importance 3. The greatest flares are sometimes rated as Importance 3+. These area limits are not strictly adhered to, but are sometimes adjusted when a flare shows abnormal intensities for its size.

The lifetime of a flare is characterized by a sharp rise to maximum intensity, sometimes described as a flash of radiation, followed by a longer decay period. The entire life of a flare may vary from a few minutes to as much as seven hours, with the average being about 20 minutes. According to Richardson 14) about 75% of the Importance 1 flares, and about 79% of the larger flares, reach maximum in less than 0.4 of their lifetime The stay at maximum is usually less than five minutes even for the flares that last several hours.

There are several methods of determining the time of maximum action of the flare. Sometimes the measurement given is the central intensity

of the Hα line, photometrically determined. Values for the intensity of that line at maximum range from about 40% to as much as 300% of the intensity of the solar disk near the flare in a neighboring continuous portion of the spectrum. (It is necessary to remember that the brightness of the solar disk at the center of Hα is only about 10% the brightness of the disk in the neighboring continuous portion of the spectrum.)

Another method is to measure the broadness of the Hα line at regular intervals. Flares are accompanied by a peculiar broadening of Hα which increases regularly with the intensity of the emission. Ellison reports that for flares whose intensity is greater than 150% of the continuum in the nearby portion of the spectrum, the Hα line develops wings which sometimes give the line an effective width of 20 A. 15) It is found that the time at which maximum broadness of Hα and the maximum intensity occur seem to be the same.

The flares themselves show very little motion either horizontally or vertically, and usually seem to lie very near the solar surface, though definitive evidence on heights is usually lacking. The sightline velocities of flares seem to be of the order of 20 km/sec., which is slow compared to the velocities of some prominences. However, at least 20% of the flares eject prominence material at very high velocities at about the time they reach their maximum. 16) A tremendous increase in Lyman-alpha probably occurs at the time of the flare and some workers have suggested that the radiation pressure forces the prominences upward. 15,16)

Aside from the phenomena we observe in flares on the sun, we find many geophysical effects that can be directly associated with flares. At the time of a flare the quality of long-distance radio reception over the entire sun-lit portion of the world undergoes a great change. The complete radio fade-out (Dellinger-Mögel effect) that occurs simultaneously with the onset of the flare, 17) has generally been explained in terms of heavy ionization of the D-region of the ionosphere causing strong absorption of the radio waves from earth which ordinarily pass unaffected through this layer. Increases in ultraviolet light from the Lyman-alpha may cause the increased ionization, but others have suggested that X-ray transitions in the coronal ions might cause the D-region effect.

There is abundant evidence that great increases in low energy cosmic rays often accompany the larger flares. 18) Sudden changes in the intensity and direction of the earth's magnetic field are noticed at almost the same time as the maxima of some flares. These are again attributed to the ultraviolet light of the flare causing ionization effects in the upper atmosphere which produce induced magnetic fields. Magnetic storms and aurorae, presumably both caused by charged particles disrupting the earth's magnetic field, are often observed from six to thirty-six hours after the flare. In addition, flares probably influence the temperature of the earth's upper air, initiate weather changes, and play a key role in numerous other related phenomena.

With the tremendous effects that flares have upon the earth, it would be advantageous if we could predict the imminence of flares. If a

close relationship can be shown between the occurrence of flares and the yellow line, it may aid us to predict the coming of flare regions from the appearance of the yellow line on the east limb of the sun, the limb over which new regions appear as the sun undergoes its 27-day rotation. In the material that follows I shall give the results of my efforts to establish the relationship between the occurrence of flares and the yellow line.

III. METHOD AND RESULTS OF ANALYSIS

A. Measurement of Coronal Spectra

The first step in the study was to obtain all the spectrograms which contained the yellow line. In the past several years there has been a careful effort at the observatory to note all the cases of the yellow line as they occur and to place these plates in separate boxes. However we feared that during the period of 1945 through 1949 there may have been some cases missed. Therefore I examined all spectrograms for this period, some 4500 of them, looking for the yellow line. This line, as mentioned before, is hard to detect because of its diffuse nature and its faintness. I held the spectra over a diffuse light source and made a careful examination of the yellow line portion of the spectrum. I conducted the examination completely independently of any previous measures of the plates or of the behavior of the spectrum in any other wavelength. In some cases the occurrence of the yellow line was doubtful, either because of high background density due to scattered sunlight, or because the faintness of the yellow line caused it to disappear in the plate fog, or for other reasons. These doubtful cases I discarded as unreliable. Eight previously unreported occurrences were found.

When a plate was found to contain the yellow line, it was set aside to be measured at a later time with all the other yellow line plates. By measurement is meant the determination of the intensity of the yellow line at different latitudes along the limb of the sun.

The spectrograph has a curved slit which, during observation is placed just outside the edge of the solar image in a concentric fashion, so that the coronal emission falls on it. In this way about 90 degrees of latitude along the limb may be covered in a single exposure. The spectrograms then contain curved lines instead of the conventional straight lines of a laboratory spectrogram. Each portion of the spectrum line arises from a different solar latitude.

To determine the intensity of any coronal line we use a photographic standard consisting of a glass plate on which appear 22 lines of graduated densities. The standard bearing these lines, whose appearance resembles real coronal lines, is placed directly upon the spectrogram and a match is made by eye between one of the lines on

the standard and the line on the spectrogram. The standard lines bear numbers which range from 1 to 65, according to the density of the line. The numbers give the "Climax Arbitrary Coronal Intensity" scale, an arbitrary scale of line emission intensity similar to the scale adopted by Waldmeier in 1938. The same method of measurement is used by the observatory for making the daily determinations of the coronal intensity. The measurement process gives reproducible results easily within the limits of the observing variables. It depends, of course, upon accurate exposure and plate-processing for the original spectrograms. The intensity of the yellow line was measured in this fashion at 2.5 degree intervals along the arc of the sun's limb.

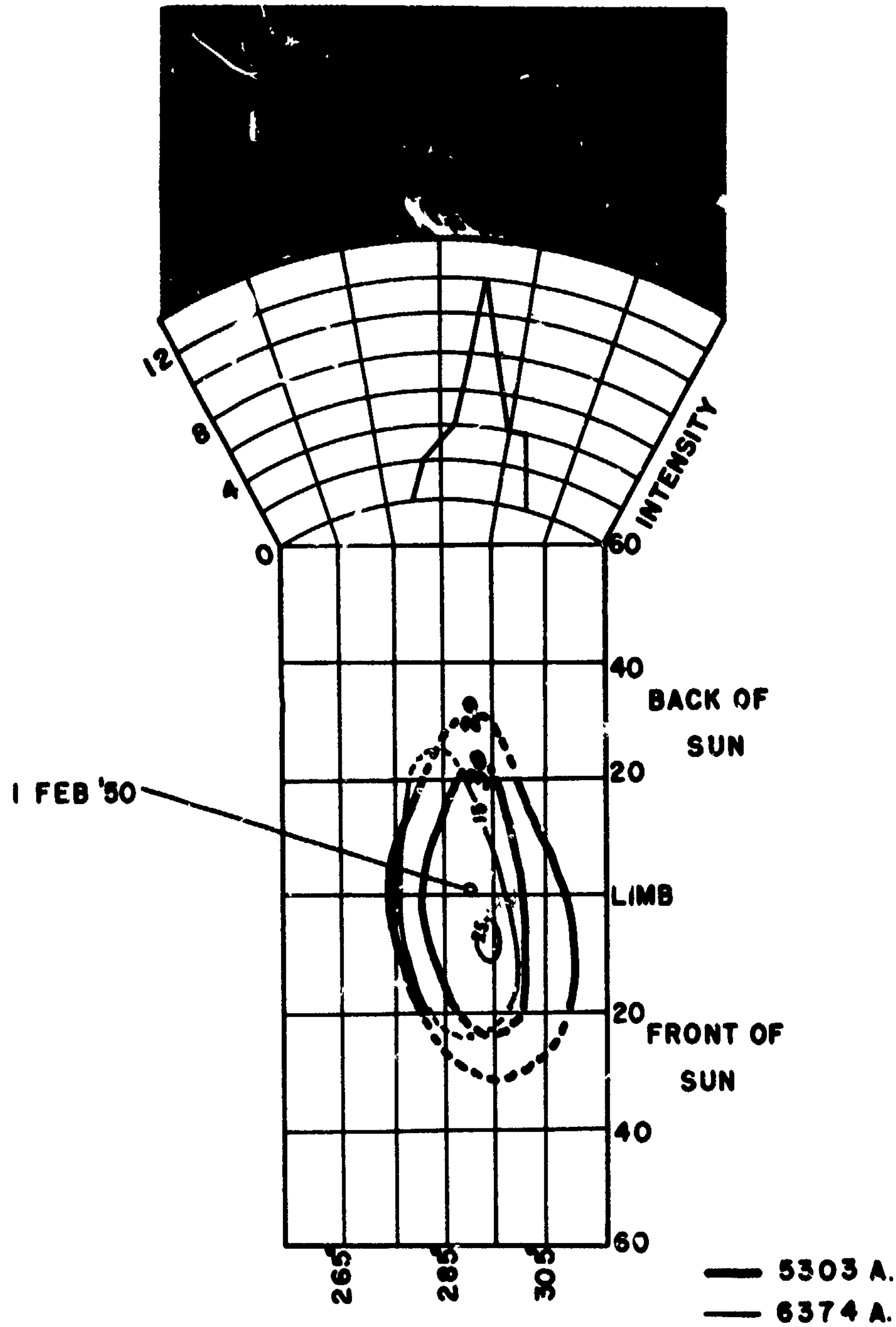
Very often there were several spectrograms containing the yellow line for the same day. When the observers were aware of the presence of the yellow line they took as many as a dozen exposures spread out over the observing day. Some of these spectra were special exposures made closer to the limb of the sun than is the ordinary practice. Since the yellow line has a sharp gradient in height, these extra plates often show the line stronger than the normally exposed plates. These plates were measured but were not used in the analysis reported here. The only plates used were those taken at the normal height above the limb and which were considered exposed and developed under standard conditions as determined by the sensitometer markings which appear on every plate.

The intensities measured in the yellow line ranged from 1 to 14 on the arbitrary standard scale, with the most common values below 4. By way of contrast the green line sometimes is as high as 50 and the red line as high as 40.

At the time of measurement, the prominence spectra and the appearance of the other coronal lines were observed. In a typical case, the prominence spectra showed bright beads of emission which were often displaced by Doppler shift from the center of the absorption line on which they ordinarily lie. In 80% of the prominences sightline velocities were seen which were considered higher than those seen in prominences in general. The prominence spectrum of the Helium D_3 line did not always have the same appearance as in the Hα line. The velocities and shape of these two lines sometimes differed which probably indicates different relative abundances of these two elements in different portions of the prominence, a question worthy of substantial independent study.

The line of HeII at 5412 A. was found in three of the prominences accompanying the yellow line. Although no systematic search has been made for this line, I observed it once in a prominence not associated with the yellow coronal line. We cannot say, therefore, that the 5412 A. line is uniquely associated with the yellow line.

Doppler shifts in the red and green coronal lines were noticed in eight of the fifty yellow line cases. This rare event has been



2 FEBRUARY 1950

FIGURE 1

seen only a few other times in the ten years the Climax observatory has been viewing the corona. We know that it is rare, because systematic search for this effect, unlike the 5412 A. line, has been made. On only one occasion did the yellow line itself display a Doppler shift, which was confirmed on several plates taken the same day. No report of this event has appeared in the literature, so far as we are aware.

From the examination of the spectra we can thus conclude that the solar condition at the time of yellow-line emission are most certainly exceptional.

B. Association of Prominences with the Yellow Coronal Line

After the yellow-line spectra measurements were completed, I made photographic prints of all prominences associated with the yellow line from prominence films taken on the yellow-line day. The prints were fastened to a polar coordinate graph which indicated the position angle of the prominence on the limb. The position angle is measured from the center of the sun with zero at the north pole and the angle increasing toward the east. (Figure 1) The yellow-line intensity was plotted on the same graph to show the comparison between yellow-line intensity and various features of the prominences.

In a number of cases the yellow-line peak seemed to be at the focal point of the moving prominence material, that is, at the center convergence for the prominence. This was not the general rule, however. No general conclusion could be reached from this portion of the analysis except that there was a prominence present at each yellow-line occurrence and that the majority of them showed the characteristic outlines of sunspot prominences.

The rectangular grid connected to the polar coordinate graph represents the portion of the solar surface in the vicinity of the limb at which the yellow line occurred. The line marked "limb" represents the limb of the sun on the day of the yellow line. The sections above the line, marked off in 20 degree intervals, represent that portion of the solar disk which had been at the limb on the preceding days, and the sections below the line represent that portion which passed over the limb on the days following the yellow line. On these maps the intensity of the red and green coronal lines, as determined at the limb, were plotted in contour fashion. This was done to give us an idea of how the other coronal lines were behaving at the time of occurrence of the yellow line. Dashed lines indicate that no coronal observations were available for that portion of the disk when it passed over the limb. A minimum intensity of 20 for the green line and 15 for the red line was chosen to keep the number of contours down and still show the activity. In 56% of the cases the green-line peak was at the same position and time as the yellow line and in 16% more of the cases the green-line maximum was within one day away and at the same latitude. The red line didn't show

such a close relationship when it came to high intensities. In fact, the red line was, at times, disappointingly low. It was noted in the study of the spectra, however, that the red line seemed to show maxima at the yellow-line position even though they were rather low compared to the heights to which the red line sometimes goes. The red line showed a high maximum as recorded on the contour maps at the same position as the yellow line in 28% of the cases. The high connection between the red and green coronal maxima and the yellow line indicates that the yellow line occurs in regions of unusual concentration of coronal intensity and not just at random. A further study of the relationship between the yellow line and the other coronal lines will be taken up at a later date by Dr. Roberts and his associates.

At the suggestion of Dr. Roberts, I plotted all the flares that occurred near the time of the yellow line on these maps. They are indicated by a circle which puts the flare at the heliographic longitude at which it occurred. The date at which the flare occurred is also indicated. In this way a flare that appeared at the same heliographic longitude as the yellow line, for instance, is plotted on the line marked "limb" even though it occurred on the disk on a day before or after the yellow line was observed.

C. Analysis of Characteristics of Associated Prominences

While this was being done, Bruno Witte, who is also working on the problem of yellow line at the observatory, compiled two reels of 16 mm. motion pictures of the prominences that occurred on the day of the yellow line and on the two days before and after the yellow line. These reels consisted of some 41 movies of different prominences corresponding to 23 cases of the yellow line. We felt that a great deal of additional information could be obtained by observing the motions of the prominences and seeing how they changed over a period of time. The motion pictures were made by taking photographs of the prominences at the rate of two, three, or six frames per minute. When the film is projected at the rate of 16 frames per second, the motion is speeded up by a factor of 480, 320, or 160 respectively, clearly showing the prominence motion. For the high velocities involved in the prominences that one usually finds along with the yellow line, we discovered that films taken at six frames per minute are the most satisfactory.

In order to obtain some sort of a description of the prominences that could be handled statistically, we decided to grade each prominence according to certain well-defined characteristics. The grading within each category was done on a basis of the degree to which the prominence displayed the specified character. We used a one to five scale, with one indicating that the characteristic was very clearly defined and five indicating that the characteristic didn't exist in the prominence. The films were examined several times in a preliminary way so that we could determine the features that had most promise of

definable character and degree and that seemed typical of our corona-associated prominences. The following characteristics were the ones we chose:

1. Construction of prominence

    a. Scattered knots — isolated concentrations of prominence material that are not fastened to any other portion of the prominence.

    b. Continuous streamers — prominence material fastened together to give the appearance of a solid stream.

    c. Massive body — the body of the prominence is a large mass of material such as is usually associated with the "quiescent" prominences.

2. Origin of the prominence material

    a. Space — the prominence gas seems to materialize out of "space."

    b. Suspended cloud — the prominence material seems to come from a gloud of gas hovering above the sun.

    c. Body on the sun's surface — the material seems to come from a body on the surface of the sun.

3. Focussing effects

    a. At the source of the moving matter — the prominence material seems to originate at one point and spread out or move in several different directions.

    b. At the terminus of the moving matter — the material seems to converge at a point on the sun's surface.

4. Curvature of trajectory — the trajectory of the moving material is highly curved.

5. Number of surges seen — the actual number of sudden ejections of prominence material upward from the surface were noted.

6. Direction of motion

    a. Downward — the prominence material is moving downward.

    b. Horizontally — the material is moving horizontally.

    c. Interacting — the material seems to be moving in opposite directions at the same time.

d. Upward — the material seems to be moving upward.

Many of the above characteristics were seen simultaneously, to a greater or lesser extent, showing that the characteristics were not in any sense mutually exclusive. In addition, the grading was quite subjective. Two people classifying the same prominences seldom agreed upon all the gradations. Five different observers graded our two reels of films according to this plan. We found, upon comparing the final results of the grading, that there were not many cases where Mr. Witte's and my grades differed by more than one unit.

Perhaps the most striking thing about these prominences is the predominance of downward motion. The first impression I got was that all the material was pouring down to the surface of the sun. The prominences seemed to be made up of knots of material travelling downward in carefully defined trajectories. Often these trajectories were completely full of material and had the appearance of solid streamers. Even in these cases, knots of matter were seen travelling downward in the stream. The solid streamers seemed to occur most frequently when the prominence had a looped shape. The prominence matter seemed to appear from space at the top of the loops and pour down the two branches. In the type of prominence in which the knots predominate, we found that the knots formed in space and travelled down slightly curved paths toward a common focal point. The knots usually moved quite rapidly as they formed. The appearance of the prominence material "out of thin air" was another predominant characteristic of these prominences. Menzel [19] and also Kiepenheuer [20] explains this phenomenon by assuming that prominence atoms are completely ionized by the high temperatures of the corona and are therefore invisible when high above the solar surface in the coronal region. When the atoms come into the cooler region nearer the sun where they pick up free electrons, they become visible.

In contrast to the downward motion, one finds sudden ejections of matter with great violence coming from the solar surface. Very often these ejections seemed to come from that same point into which the downward moving prominence material was falling. These surges occurred with velocities of up to 500 km/sec. and were sometimes sufficiently powerful to send the material completely out of the field of the telescope, a distance of about 200,000 miles. More often the material rose up and then fell back into the sun along the same path it followed on the way out. Surges are quite frequent events in the yellow-line prominences.

After the prominences were graded, as described above, they were grouped according to their position in time with respect to the yellow line. The number of films in each category is listed in Table I.

Table I					
Days Away From Yellow Line	-2	-1	0	+1	+2
Number of Films	3	7	21	6	4

An average value was obtained for each characteristic in each time group for each grader. We had hoped that we could thus detect a systematic change in the character of the prominence from the two days before to the two days after. Mr. Witte's results show slight trends in several of the characteristics with a maximum or minimum on the yellow-line day. My results and those of the other graders did not show these trends. Because of this result, I decided to abandon this approach and try something more direct.

I felt that the time lapse of two days from the yellow-line case was too short to clearly show the differences between the prominences that are present around the time of the yellow line, and other types of prominences. I therefore decided to examine prominences entirely away from the solar regions displaying the yellow coronal line. For this I chose the movies left on the reels in the film library after the yellow-line movies had been cut from them. Two reels were picked, one from the winter of 1947-1948 and one from the winter of 1949-1950. The two reels contain prominences from the time near sunspot maximum and from a period two years away from maximum, and therefore give a fair representation of the character of prominences in general chosen from the same general period as the yellow-line cases. Winter films were chosen because of the better quality of the sky in the winter and the longer length without interruptions. In the winter, the sky is usually either completely overcast or relatively clear without the scattered cumulus convection clouds that cause the summer films to be interrupted so often.

The first 42 prominence movies were chosen from these reels. Thirty were from the first reel, 12 from the second. This is approximately the same number of separate prominences as on the yellow-line reels and the running time is approximately the same, about 8500 minutes observing time. I graded these prominences on the same characteristics as the yellow-line prominences, and in exactly the same way.

The general impression one gets from these non-yellow-line prominences is entirely different from the impression left by the yellow-line movies. The motion is no longer so predominently downward but seems to show much more horizontal motion than before. The prominences usually appear to be large bodies resting on the solar surface and it is from these bodies and not space that most of the moving matter comes. Mixed in with these larger massive prominences,

generally the quiescents, there are prominences which certainly belong in the yellow-line category. All the characteristics are there: the downward motion of the streamers and knots, the surges, and the appearance of the matter from space. Considering the difficulty of observing the yellow line, these are quite probably yellow-line prominences for which the yellow line could not be seen even though it was present. This is a point which it is important to verify by observation with a spectrograph and coronagraph specially adapted for yellow-line observations, as the High Altitude Observatory plans to do later.

D. Analysis of Control Group of Non-Associated Prominences

My next effort was aimed at study of a control group of prominences not associated with observed cases of yellow-line emission. I sought to determine whether the average grades for such prominences differed significantly from the average grades for the yellow-line prominences. The results were as follows.

First I calculated the average grades for each characteristic for both the yellow-line prominences and the non-yellow-line prominences. Then the standard deviations of the distributions of grades for each characteristic were computed in the usual way. These I called σ_X the standard deviation of the sample. I then assumed that if many such sample means were computed, these sample means would follow a normal distribution about the population mean. To obtain an idea of the dispersion of sample means about the unknown population mean, I calculated the standard error of the unknown population mean using the relationship

$$\sigma_{\bar{X}} = \frac{\sigma_X}{\sqrt{N-1}}$$

where $\sigma_{\bar{X}}$ is the standard error of the unknown population mean, σ_X is the standard error of the sample and N is the number of movies. This was done for each characteristic in both groups of films. The justification for this procedure is given in "Applied General Statistics" by Croxton and Cowden.[21] If we assume that the two groups of films come from the same population, that is, that they have no inherent differences, the expected difference in means of the two groups will be zero. If a difference in means does exist, we want to know what the probability is that so great a difference could occur by chance. The standard error of the difference of two means is given by

$$\sigma_{\bar{X}_1 - \bar{X}_2} = \sqrt{\sigma_{\bar{X}_1}^2 + \sigma_{\bar{X}_2}^2}$$

where $\sigma_{\bar{X}_1}$ and $\sigma_{\bar{X}_2}$ are the standard errors of the two means. The differences in means of samples from the same population should follow a normal curve and so 99.7% of the differences in means would be within plus or minus three standard errors of the difference in means.[21] If the difference was greater than this, I considered the difference significant, that is, that there is very little chance that the observed difference in means occurred by chance and therefore

Table II

Characteristic	Y. L. Mean	Non-Y. L. Mean	$\sigma_{\bar{x}_1 - \bar{x}_2}$	$\frac{\Delta M}{\sigma_{\bar{x}_1 - \bar{x}_2}}$	Probability
Scattered Knots	2.51	3.62	0.273	4.1 σ	4×10^{-5} *
Continuous Streamers	2.63	3.55	0.244	3.7 "	2×10^{-4} *
Massive Body	3.71	2.02	0.320	4.7 "	$< 10^{-5}$ *
Matter from Space	1.73	3.62	0.312	6.1 "	$< 10^{-5}$ *
Matter from Suspended Cloud	4.39	4.17	0.760	0.76"	5×10^{-1}
Matter from Body on Surface	3.85	2.40	0.340	4.3 "	2×10^{-5} *
Focus at Source	3.22	4.24	0.256	4.0 "	6×10^{-5} *
Focus at Terminus	2.34	3.38	0.272	3.8 "	14×10^{-5} *
Curvature of Trajectory	2.71	3.52	0.250	3.2 "	13×10^{-4} *
Downward Motion	1.41	2.83	0.257	5.5 "	$< 10^{-5}$ *
Horizontal Motion	3.90	3.21	0.290	2.4 "	16×10^{-3}
Interacting Motion	4.46	4.57	0.214	0.5 "	6×10^{-1}
Upward Motion	4.12	4.57	0.220	2.0 "	5×10^{-3}

* = Considered a significant difference.

the two groups of prominences had different observable characteristics. The results of this analysis are given in Table II. The probabilities listed in the table are the probabilities that a difference in means as large as, or larger than, the observed difference could occur by chance.

We can obtain several kinds of information from Table II. We can determine from the value of the mean just how common a certain characteristic is. A low mean value indicates that the characteristic is strongly shown and a high mean indicates that the characteristic is weakly shown. From the difference in means and the standard error of the difference, the significance of such a difference can be determined. For instance, in the case of scattered knots, the yellow-line prominences have a low mean value (2.51) while the other prominences have a significantly higher value (3.62) indicating that the yellow-line prominences show many scattered knots and the non-yellow-line prominences relatively few. The same is true of the characteristic of continuous streamers which the yellow-line prominences possess strongly while the non-yellow-line prominences show less tendency toward this characteristic. The non-yellow-line movies on the other hand were made up of a large number of prominences with massive bodies which were the source of much of the moving material.

The yellow-line prominences did not show many massive bodies and most of the prominence material appeared in space as is indicated by the very low value of 1.73 for the mean of this characteristic. The low values for the means of the downward-motion characteristic in both sets of prominences as compared to the means of the other motion characteristics shows that prominence motion in general is downward. However, this characteristic is much more strongly pronounced in the yellow-line prominences. The downward-moving matter in the yellow-line prominences shows a slight tendency to originate in a small region (focussing at the source) and a much stronger tendency to focus at the point where it reaches the solar surface. In the non-yellow-line movies the matter showed only a slight tendency toward focussing at the terminus and almost no tendency toward focussing at the source. The yellow-line prominences had trajectories which were more sharply curved than the non-yellow-line movies.

The horizontal motion which, at first glance, seemed to be much stronger in the non-yellow-line prominences is not significantly different by the standards chosen for significance although the mean is somewhat lower. The false impression could easily have come from the lessening of the downward motion and motion in general which made the horizontal motion stand out more strongly.

Interacting motion, matter mutually exchanged between two or more prominences, and upward motion, were about equally weak in both groups. The appearance of matter from a cloud suspended above the

surface of the sun is a rare event in both groups of prominences and there is no significant difference in the small degree to which this characteristic is present in both.

In order to evaluate the information obtained from the observation of the surges, the factor of observation-time was introduced. The number of surges in each prominence was divided by the number of minutes of observing time for that prominence. In order to avoid small fractions I multiplied these numbers by 1000 to get the number of surges per 1000 minutes of observing time per prominence. These values were handled in the same way as the grades for the other characteristics. For the yellow-line prominences the mean was 7.05 surges per 1000 minutes per prominence with a standard error of the mean of 1.45. The mean for the non-yellow-line prominences was 2.05 with a standard error of the mean of 0.61. The standard error of the difference in means is then 1.57. The probability of a difference as large as, or larger than, the one observed occurring by chance is 1.4×10^{-3} or a little better than one chance in 1000, which is considered significant.

With the probabilities as small as they are for most of the characteristics, I feel it is safe to say that the general impression of these prominences is essentially correct and that easily distinguishable differences in the two groups exist for the production rate of surges and for all characteristics of Table II marked by the symbol *.

E. Yellow Line and Limb Flares

When the flares were plotted on the coronal contour maps mentioned earlier, I found a large number of coincidences between the yellow line and flares occurring near the limb on the yellow-line day. At the time I decided to investigate this matter a little more closely. I arbitrarily called any flare which appeared within five degrees of the limb of the sun, a limb flare. This would put the position of the flare no more than half a day's rotation from the limb, which seems to be a reasonable restriction due to the short life of the yellow line. If the flare were much further from the limb than this, and if the yellow line were to originate in or near the flare, the yellow line might not be visible by the time it rotated into view.

I compiled a list of all such flares occurring from 1946 through 1950 from the Quarterly Bulletin of the International Astronomical Union. The data in the Bulletin is collected from observing stations all over the world, so that on days when weather permits, complete coverage of flare activity is available for any 24-hour period. These stations reported a total of 165 days on which flares occurred within five degrees of the limb during the five years in which I was interested.

The coverage of coronal observations from Climax was not nearly

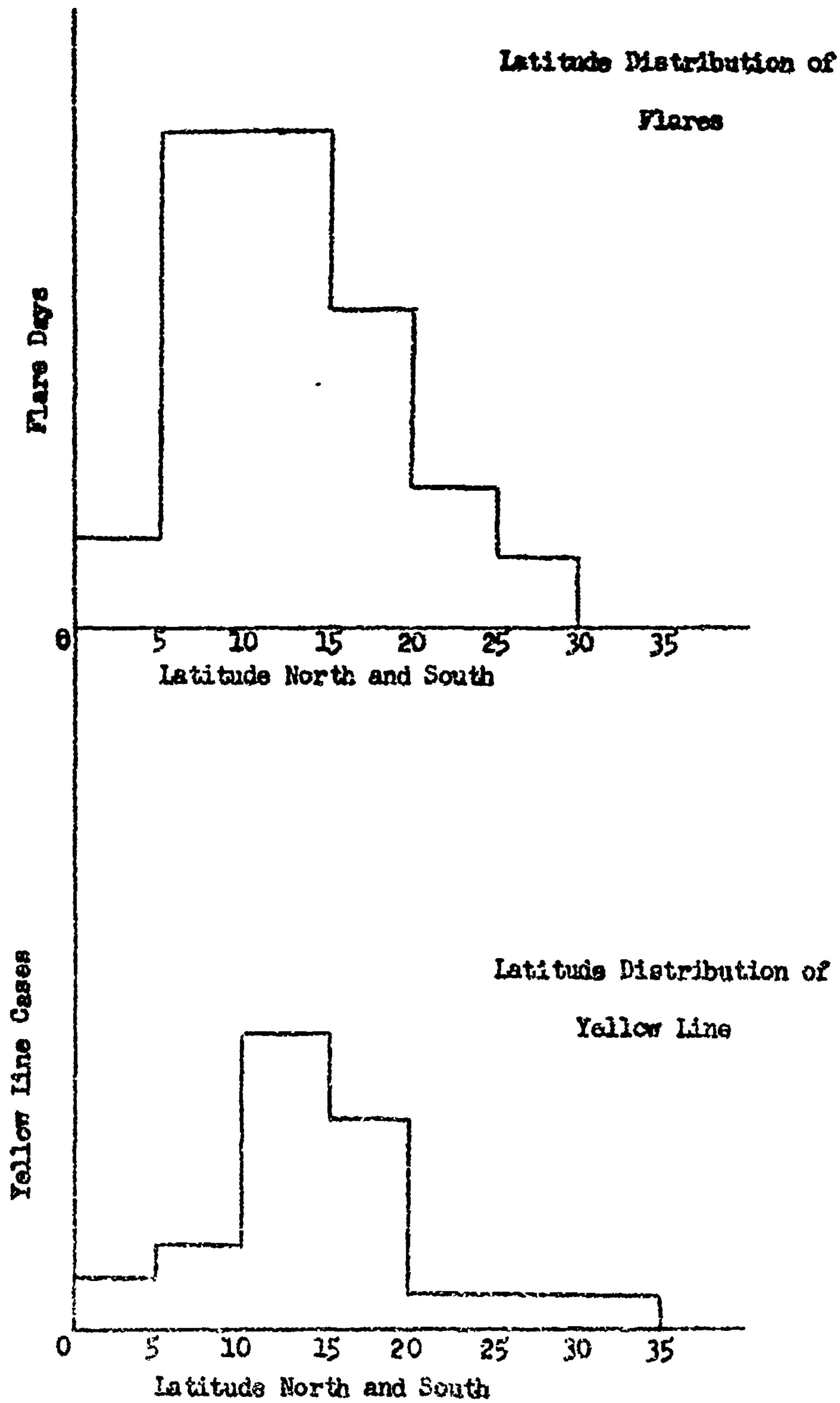

Latitude Distribution of
Flares
Flare Days
0
5
10
15
20
25
30
35
Latitude North and South
Latitude Distribution of
Yellow Line
Yellow Line Cases
0
5
10
15
20
25
30
35
Latitude North and South

Figure 2

as complete as the flare coverage, so all flares which occurred on days when there were no coronal observations were discarded. This reduced the number of days on which limb flares occurred to 91 for the 938 Climax observing days. I assumed that the weather at Climax is independent of the conditions on the sun and therefore the selection of the data in this manner is a random selection.

The yellow-line data contained the 43 cases of yellow line that occurred from 1946 through 1950.

An analysis of the latitude distribution of flares near the time of the yellow line showed that all but a few of the flares occurring within two days of the yellow line were within five degrees of latitude of the yellow-line maximum. These few were all within ten degrees of the yellow-line maximum. This alone suggests a significant association, but I wished to investigate the matter more closely.

In 13 cases the yellow line and a flare occurred on the same day and within five degrees of each other, and in 18 more cases the yellow line and the flares were no more than two days apart and within five degrees of latitude of each other. Only 12 yellow-line cases seemed to have no flares associated within two days. Closer examination revealed that all but one of these cases occurred in the winter or early spring when the daily flare observing time may get as low as one hour. It is possible that unobserved flares associated with the yellow line occurred during this time.

To determine the probability of 13 coincidences between the yellow line and flares we must know the latitude distribution of both the flares and the yellow line. Referring to Figure 2, which gives the latitude distribution of the 43 yellow-line cases and the 91 flare days, we see that the most favored zone for the flares is the belt between 5 and 15 degrees north and south of the equator and that no flares occurred more than 30 degrees from the equator. We also see that the favored belt for yellow line is that region between 10 and 15 degrees north and south of the equator and that the yellow line is confined to a region within 35 degrees of the equator. This shows that the two phenomena are confined to the sunspot zone, and that neither is distributed over the whole solar sphere. In this graph the flares and yellow-line cases at the same latitude north and south of the equator are grouped into a single class. To determine the probability of 13 coincidences with the shown distributions would be a tedious task. I shall therefore make some simplifying assumptions which will give me a probability that is at least as large as the actual probability and will make the calculations much simpler. I will assume that the probability of a flare or yellow line occurring in any latitude where they are found, is the same as the probability of occurring in the most favored latitude belt.

Since 56 flare days occurred in the latitude belt ranging from

5 to 15 degrees on either side of the equator, a 20 degree belt, the probability of a flare occurring anywhere on the limb in the 60 degree-wide flare belt would be $3 \times 56/938$ or $168/938$. In actuality the probability would generally be even less. For a yellow line to occur within 5 degrees of the flare, it must fall within a given 10 degree latitude belt. The most favored zone for yellow line was the belt ranging from 10 to 15 degrees on either side of the equator, a 10 degree belt in which 17 yellow lines occurred. We will therefore use this probability for all the latitude belts. Thus the probability of a yellow line occurring within a given 10 degree latitude belt is $17/938$. This, too, over-estimates the probability, so our calculation is on the safe side again. The probability of both the flare and the yellow line occurring on the same day and within 5 degrees of each other is then $168/938 \times 17/938 = 0.0032$. Since the probability of a single coincidence is so small it is reasonable to expect the coincidence to follow a Poisson distribution. In a Poisson distribution, the probability, "P" of obtaining "r" successes in "n" trials is

$$P = \frac{(np)^r e^{-np}}{r!}$$

where p is the probability of a single success. 22)

We would like to know the probability of obtaining 13 or more coincidences. To do this we must sum the individual probabilities from 13 coincidences to 938 coincidences. Thus the probability of 13 or more coincidences is given by

$$e^{-np} \sum_{r=13}^{r=938} \frac{(np)^r}{r!}$$

This may be approximated with very little error by

$$e^{-np} \sum_{r=13}^{\infty} \frac{(np)^r}{r!}$$

if the number of samples is sufficiently large. The error in this case would be less than

$$\frac{e^n p^{n+1} (1-p)^{-1}}{\sqrt{2\pi (n+1)}} e^{-np}$$

22). For the 938 sample days in my case the important factor in this expression is $e^{938} \cdot p^{939}$ or approximately $(2.718 \times 0.0032)^{938} = (0.0087)^{938}$ 10^{-1876}. The error in this approximation is therefore negligible.

Referring to Molina's tables of the Poisson summations, the probability for 13 or more coincidences when the most probably number of coincidences, (np), is (938)(0.0032) or 3.03 is given as 0.000018 or 1.8×10^{-5}. 21)

Since the probability is as small as it is, there is little doubt that the coincidences are real and not chance occurrences. Therefore, there is almost certainly a definite physical relationship between the yellow line and flares.

IV. CONCLUSIONS AND SPECULATIONS

Since about 70% of the yellow line cases considered occurred either with a flare or within two days of a flare, and the other 30% could quite easily have had unobserved flares associated with them, it might be possible to predict the arrival of a flare-producing region by observations of the yellow line at the east limb of the sun. This would be especially advantageous in the winter when weather conditions restrict continuous flare observations. The life of the yellow line is long compared to the life of a flare and so only a ten-minute coronal observation daily probably would be sufficient to detect the yellow line while the chances of detecting a flare in even a few hours' observations would not be very good. A prediction of this sort would be a great help to the radio warning services whose results depend strongly upon knowing when flare regions are present.

The prominences accompanying the yellow line are easily distinguishable from prominences in general, by their shape and motion. It may be possible, therefore, to predict the presence of the yellow line by observations of the prominences alone. Prominences are visible through light cirrus clouds and dust conditions that render the observation of the corona impossible. This would, of course, be of great practical significance. There are indications that the red and green coronal lines have maxima at the same time as the yellow line appears and so it might be possible to estimate the conditions in the corona at times when direct observations are not possible. I strongly recommend an investigation into the relationships between the red and green lines and the yellow-line prominences. If such a relationship is established quantitatively, it too would be a great help to the radio propagation services, since a knowledge of the conditions in the corona are needed to make good predictions.

V. ACKNOWLEDGEMENTS

My deepest thanks are due Dr. W. O. Roberts for suggesting this problem and for his assistance and direction in carrying it out. Also I wish to express my gratitude to Bruno Witte for his helpful suggestions and criticisms, and to the observers at Climax and Sacramento Peak for their part in the observations used. To Harvard University I express appreciation for permission to examine the spectra and films from the Sacramento Peak Observatory program operated by Harvard under contract with the Geophysical Research Directorate of the Air Force Cambridge Research Center. Collateral support of my work came also from Research Corporation and the National Bureau of Standards through their support of research in progress at High Altitude Observatory.

Finally I wish to thank the Office of Naval Research for their support of my research as a portion of a larger program of work at High Altitude

observatory involving the study of relationships between the yellow coronal line and the solar and terrestrial phenomena that may be associated with it. Without this help, I could not have undertaken to work on this most interesting and significant program.

Frederick P. Dolder

High Altitude Observatory
Boulder, Colorado

29 August 1952

Approved for Submission as
Technical Report

Walter Orr Roberts

Walter Orr Roberts, Director
High Altitude Observatory

10 November 1952

VI. BIBLIOGRAPHY

1) R. v.d. R. Woolley and C. W. Allen, "The Coronal Emission Spectrum", Monthly Notices of the Royal Astronomical Society, 58, 292, 1948.

2) H. C. van de Hulst, "Zodiacal Light in the Solar Corona", Astrophysical Journal, 105, 471, 1947.

3) B. Lyot, "A Study of the Solar Corona and Prominences Without Eclipses", Monthly Notices of the Royal Astronomical Society, 99, 589, 1939.

4) W. O. Roberts, "Association of Corona with Prominence", Astrophysical Journal, 108, 523, 1948.

5) W. O. Roberts, "Sunspot Prominences and the Yellow Coronal Line", Astrophysical Journal, 115, 488, 1952.

6) M. Waldmeier, "Das Verhalten der Koronalinie 5694.42 A", Astronomische Mitteilunger der Eidgenossischen Sternwarte Zurich, Number 146, 6, 1945.

7) B. Edlen, "Die Deutung der Emissionalinien im Spektrum der Sonnenkorona", Zeitschrift für Astrophysik, 22, 30, 1940.

8) M. Waldmeier, "Comparative Observation on the Corona Lines 5303, 5694 and 6374 A.", Zeitschrift für Astrophysik, 20, 172, 1940.

9) M. Waldmeier, "Die Neue Koronalinie 5445 A.", Zeitschrift für Astrophysik, 29, 29, 1951.

10) I. S. Shklovsky, "Computation of the Concentration of Coronal Ions in Ground Quantum States", Annals of the Crimean Astrophysical Observatory, 5, 86, 1950.

11) A. M. Naqvi, "Emission Lines of the Solar Corona", Astronomical Journal, 56, 135, 1951.

12) R. H. Garstang, "On the Coronal Lines λλ 5445, 5694 and 4086", Astrophysical Journal, 115, 349, 1952.

13) E. Pettit, "The Properties of Solar Prominences as Related to Type", Astrophysical Journal, 98, 6, 1943.

14) R. S. Richardson, "Characteristics of Solar Flares", Astrophysical Journal, 114, 356, 1951.

15) M. A. Ellison, "Characteristic Properties of Chromospheric Flares", Monthly Notices of the Royal Astronomical Society, 109, 3, 1949.

16) R. G. Giovanelli, "Solar Eruption", Astrophysical Journal, 91, 335, 1940.

17) J. H. Dellinger, "Sudden Disturbances of the Ionosphere", Proceedings of the Institute of Radio Engineers, 25, 1253, 1937; Terrestrial Magnetism, 42, 49, 1937.

18) S. E. Forbush, T. B. Stinchcomb, and M. Schein, "The Extraordinary Increase of Cosmic Ray Intensity on November 19, 1949", Physical Review, 79, 501, 1950.

19) D. H. Menzel, "Colloquium on Problems of Solar Physics", Observatory, 70, 174, 1950.

20) K. O. Kiepenheuer, "The Nature of Solar Prominences", Publications of the Astronomical Society of the Pacific, 63, 161, 1951.

21) F. E. Croxton and D. J. Cowden, Applied General Statistics, Prentice Hall, New York, 1946, pp. 313-321.

22) H. Levy and L. Roth, Elements of Probability, Clarendon Press, Oxford, 1947, pp. 143-144.

23) E. C. Molina, Poisson's Exponential Binomial Limit, D. Van Nostrand Co., New York, 1943.